

# Near-Earth Object (NEO) Characterization at the Maui Space Surveillance System (MSSS)

Paul Kervin<sup>††</sup>, Daniel O'Connell<sup>†</sup>, Paul Sydney<sup>†</sup>, SSgt. Robert Medrano<sup>††</sup>, Daron Nishimoto<sup>†</sup>,  
John Africano<sup>†</sup>, Edward Tedesco<sup>‡</sup>, Dr. John Lambert<sup>‡‡</sup>

<sup>†</sup>Rocketdyne Technical Services, 535 Lipoa Pkwy., Kihei, HI 96753

<sup>††</sup>Air Force Maui Optical Station, Phillips Laboratory, 535 Lipoa Pkwy., Kihei, HI 96753

<sup>‡</sup>Mission Research Corporation, One Tara Blvd., Nashua, NH 03062

<sup>‡‡</sup>BNA Space Operations, 1250 Academy Park Loop, Suite 130, Colorado Springs, CO 80910

## ABSTRACT

The Air Force Maui Optical Station (AMOS), located at the Maui Space Surveillance System (MSSS), has demonstrated follow-up astrometry and photometry for near-earth objects (NEOs), with results published in the Minor Planet Circulars. Although this information is important for the cataloging of all NEOs, it does not provide all of the data needed to assess the potential hazard posed by these objects, i.e. composition, size, shape, and dynamics. AMOS has increased its capability by adding a six position filter wheel (in conjunction with the University of Arizona), for use on the Jet Propulsion Laboratory's CCD camera mounted on the MSSS 1.2 meter telescope.

The paper provides the rationale for three-color photometry for determination of NEO characteristics, as well as preliminary results of the observations of several NEOs and main-belt asteroids. It also discusses the design of a photo-polarimeter, to be built in the near future, which will add more capability to AMOS, and determination of albedo and size of NEOs of particular interest to both the scientific and government communities.

## 1. Introduction

The Earth continually encounters interplanetary debris of various sizes, and evidence that the Earth may be impacted by a devastating asteroid is increasing rapidly. It is estimated that we have discovered only about seven percent of the "approximately 2,000 near-Earth objects (NEOs) larger than one km diameter" (Morrison, 1995) which can potentially intersect with the Earth's orbit. Such a collision can cause much damage including the loss of life. Moreover, a collision with an object two or more kilometers in diameter can be catastrophic to the Earth's ecosphere and is estimated to occur about every 300,000 years.

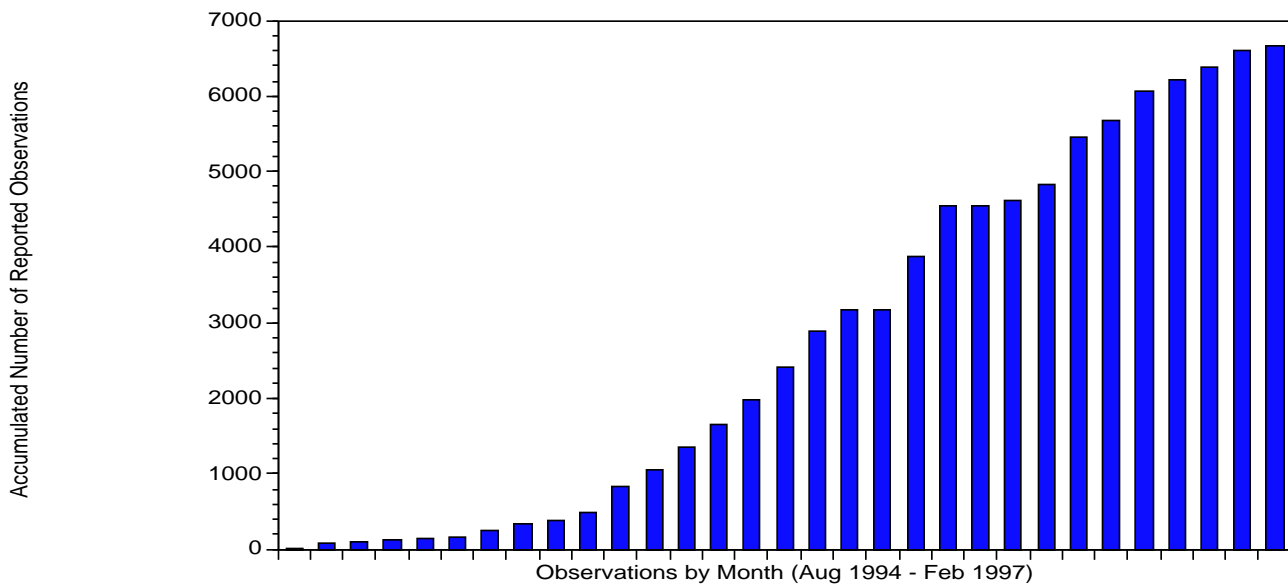
The determination of whether an NEO is an Earth-crossing asteroid (ECA) is unclear until an accurate orbit is calculated. There are difficulties in defining an accurate orbit for an NEO due to the influence of the major planets and their limited visibility. Over 250 ECAs have been detected and while the probability of an undiscovered Earth approaching asteroids larger than the largest known ECA (1627 Ivar, 8km) is statistically insignificant, our knowledge of the population of smaller, but still hazardous ECA's is far from complete. Although the Spaceguard Program, the congressionally-directed 1992 "Spaceguard" study headed by NASA, has yet to be funded, several on-going search programs

support ECA discoveries. The search programs are, the Spacewatch Program at Kitt Peak, the Palomar photographic surveys, the Near Earth Asteroid Tracking (NEAT) effort by Jet Propulsion Laboratory (JPL), and the Lowell Observatory Near Earth Object Search (LONEOS) effort. In addition to the search effort and ECA discovery programs, follow-up observations are required to refine the orbits of newly discovered objects and to characterize their sizes and compositions.

Since the Fall of 1994, Phillips Laboratory has conducted programs at the Maui Space Surveillance System (MSSS) and the Remote Maui Experimental (RME) Site to pursue the development, implementation and application of techniques for astrometric and photometric measurements of both near-Earth and main belt asteroids. The success of the on-going efforts made to automate scheduling and data reduction of observations has resulted in significant improvements in astrometric and photometric accuracy, while reducing manpower requirements. For example, in 1996, Phillips Laboratory contributed follow-up data on 3,062 objects, compared to 2,284 the previous year. Figure 1 shows the cumulative sum of the number of monthly observations sent to the Minor Planet Center (MPC) by month. From the cumulative history, it is clear that observations were limited over the first 10 months of the Phillips Laboratory follow-up program. However, in the past year, an average of more than 400 observations per month have been collected with month to month variation due to equipment maintenance and poor weather. In addition, Phillips Laboratory is also exploring the feasibility of using low cost commercial off-the-shelf (COTS) technology to supplement and complement the MSSS and Space Surveillance Network (SSN) capabilities for asteroid follow-up and electro-optical satellite metric data collection.

Currently, Phillips Laboratory is using the MSSS 1.2-meter telescope and a CCD camera on loan from JPL. Asteroid follow-up observations are performed in support of the JPL Palomar and NEAT efforts, the Spacewatch program, and the MPC critical list. In the course of the follow-up observations, the MSSS has been detecting uncataloged asteroids and has been credited with 400 new object discoveries, nearly half of which have been given MPC designations. The follow-up observing performed at MSSS is unique in that the observations are routinely made three hours per night, 5 nights per week, throughout the year. This nightly capability is especially critical in supporting the follow-up of small near Earth asteroids because of their high angular rates and short observing window. Most astronomical observatories are limited to short, infrequent observing periods.

**Figure 1. Cumulative Sum of Asteroid Observations**



Following on the success of automating the scheduling of follow-up observations on the 1.2-meter telescope, and the automation of the processing of follow-up data obtained from the JPL CCD camera, Phillips Laboratory has defined, designed, implemented, and is currently testing the Raven system, a low cost, COTS technology high-performance surveillance sensor. The Raven system was designed to be easily deployed thus, providing the ability to fill the gaps in the satellite space surveillance network. The mobility of Raven also allows for worldwide distribution of automated observing sites for complete orbital follow-up data of ECAs.

## **2. Current Asteroid Follow Up Systems**

### **2.1 MSSS 1.2-meter Telescope**

To date, most of the Phillips Laboratory observations have been obtained using the JPL CCD camera system and a coronagraph with focal reducing optics supplied by the University of Arizona's Lunar and Planetary Laboratory. The coronagraph and CCD camera system are mounted at the bent Cassegrain focus of the 1.2 meter telescope. At the heart of the CCD camera system is a Tektronix TK1024 chip, 1024 x 1024 pixels, having a quantum efficiency of about 90%, and spectral response from 300 nm to 1000 nm. The effective field of view (FOV) is about 13 arc minutes square. The CCD camera system is controlled by a DEC Workstation, designed for astronomical research. It has a slow read time of approximately 30 seconds per frame providing very low read noise. This system routinely observes objects fainter than 21st magnitude with 300 second exposure times.

Three hours of telescope time is allocated nightly allowing the collection of position and brightness data on approximately 25 objects. Each astrometric observation consists of two exposures taken at the same sky position, usually with exposures times of 300 seconds or less, separated by about an hour. These exposures are normally obtained through a Johnson R filter to match the CCD's response and minimize sky background.

## **2.2 Raven COTS System**

The concept of the Raven Network Program is to explore the feasibility of using low cost COTS technology to increase the capabilities of existing MSSC and SSN assets by off-loading the tasking/observation burden from the larger, more capable telescopes to inexpensive, smaller telescopes. Some of the applications which could utilize the Raven Network are ECA follow-ups, metrics, space object identification, orbital debris, phase angle studies, inter-site calibration, geosync coverage-gap filler, and optimized event coverage. The Raven systems were also designed to be easily deployable, providing the capability to accumulate full ECA follow-up orbital and characteristic data.

The Raven system consists of a Paramount equatorially mounted 16-inch telescope, having an f/3.3 primary mirror and a Santa Barbara Instrument Group (SBIG) ST-8 CCD mounted at prime focus. The format of the ST-8 is 1534 x 1020 pixels (9 x 9 um each), having a spectral response from 400 to 1000 nm with a peak quantum efficiency of 40%. The field of view provided by this system is 21 x 31 arcminutes or 1.2 arcseconds per pixel. A 5 position filter wheel allows multi-spectral photometric observations to determine compositional characteristics of objects. A second CCD, mounted adjacent to the imaging CCD in the ST-8 camera, serves as a tracking CCD. Frames are continually exposed at a rate of 1Hz, providing a centroid error signal to the telescope drive system to correct low frequency tracking errors. The Paramount telescope is controlled by The Sky software and a full sky mount model is performed using T-Point software. The combination of the Paramount encoder system and T-Point pointing yield accuracies of 30 arcseconds or better. The CCD camera is controlled by The SkyPro software, and objects as faint as 18th magnitude have been detected with 300 second exposure times. The Sky, T-Point and SkyPro are COTS software products produced by SoftwareBisque of Golden, Colorado. Accurate timing of 10 milliseconds or better is achieved on the Raven system using a COTS GPS receiver. The drive signal to open and close the CCD shutter triggers the GPS timing board to record the time at each instant.

Each Raven system will be housed in a 10 foot fully automated dome. The domes are slaved to the telescope mount and include weather stations that close the dome in case of inclement weather. This feature provides one of the final links towards a fully automated remotely operable telescope / dome / scheduling / data reduction system.

## **3. CONCEPT OF OPERATIONS**

The operations of the 1.2 meter JPL CCD and Raven systems are divided into several distinct phases. First, orbital data on all object requests are extracted from an on-line database and their visibility is computed within a selected observation time period. Based on their priority and visibility, the objects are then ordered in the observation schedule to minimize telescope motion and the air mass of the observation. Then the observations are made. The data is collected and stored, then each digital image is analyzed and the equatorial positions (RA and Dec) of all detected objects are computed. The object positions and rates are compared against predicted values for quality control. Finally a report is generated in a defined format, such as Space Command B3 format or Minor Planet Center (MPC) observational format.

### 3.1 Scheduling

Over the past year, MSSS has provided minor planet follow-up observations to several organizations, including JPL, Spacewatch, and University of Arizona. With our limited resources, scheduling sufficient observations for this diverse group is a challenge each night. Most requests for MSSS observations are received via email. Our approach to automated scheduling included the following tasks:

- Organize all pertinent information into relational databases.
- Generate requests and compute orbits for any newly discovered MSSS objects.
- Import email requests into a *requests* database and store any orbital element information for new objects in an *orbit* database.
- Prioritize requests by object type, arc length of observations, last observation date, requesting agency, and types of observations. With the introduction of asteroid characterization, types of observations may include multicolor photometry and light curves.
- Select only those objects within our viewing window.
- If the moon is visible, reject any objects fainter than its surrounding lunar sky background.
- Select exposure time for each observation based on its magnitude.
- If all-sky photometry is required, embed a series of calibration star fields in the observation schedule.
- Sort selected observations to minimize telescope mount motion.
- Generate a nightly mission plan in both hardcopy and electronic form. The electronic form is actually a “logging” application, where the operator can indicate when each object field is acquired and any objects that are visually detected.

### 3.2 Analysis

Analysis of each digital image can be delineated into a series of operations, including detection of stellar-like objects and streaks, determination of the image’s astrometric or “plate” solution, and computation of each image’s photometric solution, converting an object’s photon count into a visual magnitude or signature.

**Object Detection .** First, the mean sky background and standard deviation for each image is computed. Our analysis software then provides two methods for the detection of stellar-like objects. The first uses tools from the Image Reduction and Analysis Facility (IRAF), an astronomical analysis package developed over the past 15 years at the National Optical Astronomy Observatories in Tucson, Arizona. In particular, an IRAF tool called DAOFind, based on the work of Stetson (1987, 1990), convolves a Gaussian of a nominal full width half maximum (FWHM) with the input image and selects any pixel locations whose value is above the sky background by a given number of standard deviations, while rejecting candidate stars outside the preset limits for roundness and sharpness. The second technique was developed at the Côte d’Azur Observatory in Nice, France and is similar to the DAOFind task, except the convolution kernel used is called Difference of Gaussians (DOGS). This kernel fits the definition of a wavelet transform due to its null mean and regularity. By assuring zero mean in the output convolution, the DOGS kernel allows setting a lower star detection threshold, since it eliminates variation in the background across the image. Based on comparisons made over several months, detection using the DOGS kernel is much more sensitive than a Gaussian kernel in

detecting faint objects, but has a higher incidence of rejecting saturated stars as cosmic rays due to the transient nature of the kernel.

During sidereal telescope tracking, ECAs and earth-orbiting satellites appear as streaks in the CCD image. With significantly bright objects, the stellar detection algorithm identifies the object streak as a series of stars. This line of pixel detections is then determined to be an object streak using the Hough Transform algorithm, which maps the binary image of detections into a slope/y-intercept space. Detection pixels with the same slope and y-intercept accumulate at the same pixel in Hough Transform space. As a result, accumulation points above a fixed threshold are detected as streaks.

**Astrometry.** In the past, the AMOS astrometric processing has required the intervention of an analyst to assure proper alignment between the measured and catalogued stars as well as to identify and mark the tracked object. The total processing for each image was generally accomplished within 2 to 3 minutes. Recent development efforts have focused on techniques to automate all tasks in the astrometric and photometric processing including:

- Registering these stars against their catalogued star positions.
- Computing the “plate solution”, while rejecting poorly matched stars.
- Compute an approximate visual magnitude of all objects, even in crowded star fields.
- Detect objects that have moved between pairs of exposures taken at different times.
- On “photometric” nights, use instrumental magnitudes measured from calibrated star fields, such as the Landolt Standard Stars (Landolt 1973 and Landolt 1992), to compute an all-sky photometric solution, including the zero point, extinction coefficient, and color correction, Budding (1993).

A version of this processing software is in operation, which achieves most of the objectives described above. The algorithms are chosen to be robust with the output compared against nominal values and calibration references to assure accuracy. The automated processing is designed to operate on images acquired in a variety of seeing conditions and sky backgrounds. The basic steps for automated astrometry and photometry processing for each image is as follows:

- Using the detected star positions, perform aperture photometry over each selected pixel location to provide a first order estimate of each star’s relative brightness.
- Select the  $N$  brightest stars that have no neighbors within a given number of pixels and compute a nominal image point spread function (PSF) of a specified functional form, (Gaussian, Lorentz, Moffat, or a combination), with a lookup table of residuals. The estimated image PSF can be selected to vary by first or second order across the image.
- The processing uses estimates of each star’s PSF matched against the image PSF to determine its position and instrumental magnitude.
- With the nominal boresight of the image in RA and Dec recorded, select catalog stars within the nominal FOV of the image from a star catalog, such as the Hubble GSC or USNO catalog. Most pattern-matching algorithms are sensitive to matching against reference stars that are not within the image. As a result, catalog star selection ensures that any stars chosen will be present in the image given nominal telescope pointing errors. The catalog stars’ equatorial

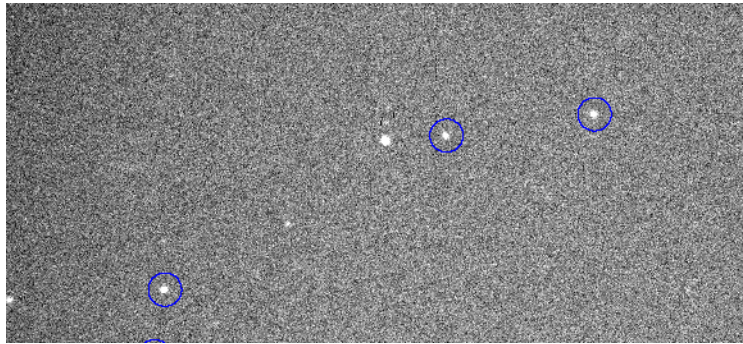
positions are then converted into pixel coordinates in the image using a nominal plate solution, derived from previous observations. By using previous plate solutions, fixed image boresight offsets, camera rotations, and higher aberrations can be eliminated.

- Match the catalog stars against all the measured star positions using Gauss' triangle algorithm and determine the center, rotation, and scale of the image. In the case of less than 4 reference stars, a simple shift-invariant pattern match algorithm is used.
- With the telescope pointing error measured, reselect all reference stars within the entire FOV and repeat the pattern matching step maximizing the number stars used in the "plate solution".
- Using the catalog star's RA and Dec values matched with its measured pixel positions, compute a "plate solution" of a given order depending upon the number of reference stars present using a "least squares" method.
- Calculate the RA and Dec of each reference from its pixel position using the computed plate solution and compute residuals between this derived RA and Dec. If any reference star's residual error is larger than some value and there are sufficient reference stars present, remove this star from the plate solution and repeat the previous step.
- Once a sufficient plate solution has been derived, compute the position of all stars detected within the image and any selected pixel positions, storing each object's RA, Dec, and instrumental magnitude for a given image.

Repeat these steps for all images of a given star field. Match the recorded object position between the images and flag non-matching objects as possible minor planets. Caution must be taken to reject any ghosts in the image by matching the symmetry of the moving object against sufficiently bright stellar objects in a sequence of images. Figure 2. displays the results of the automated astrometric processing. The stars delimited by circles indicate the matched catalog stars used to compute the plate solution. The image was acquired during sidereal tracking, so the streak in the image is a satellite moving relative to the background stars. By converting the pixel positions to RA and Dec values at the start and end of the streak, satellite metrics can be computed based on the recorded times at the opening and closing of the camera shutter.

Computing the object's position and magnitude using the PSF has several advantages. First, while centroid estimates can conservatively achieve an accuracy of 0.25 pixels, match filter estimates using PSFs nominally result in position estimates to within 0.1 pixels. Second, PSF estimates allow the use of "Crowded Field Photometry" techniques developed by Stetson (1987) and Stetson et al (1990), assuring more accurate magnitude estimates in star-dense fields. Third, it may be possible to sharpen the image with this PSF using image restoration algorithms, such as Maximum Entropy or Lucy.

**Figure 2. Automated Astrometric Processing on a Satellite Image.**



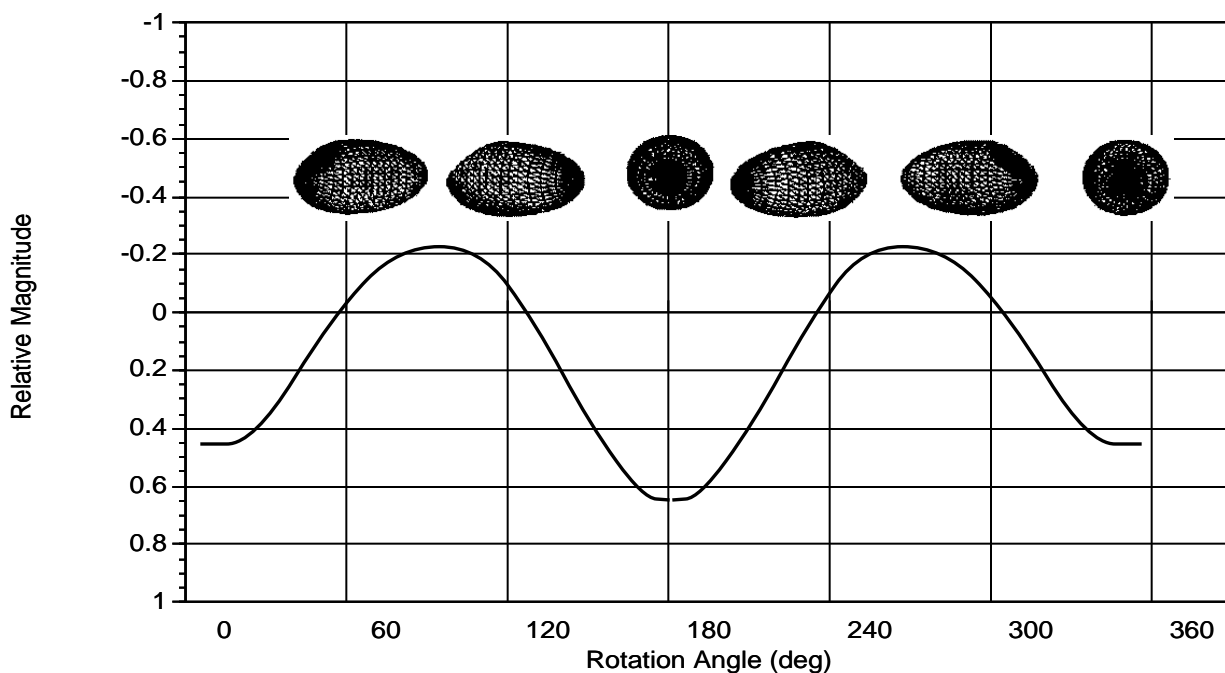
**Photometry.** It has long been recognized that asteroids are diverse in composition. Broad-band photometric systems have been used to classify asteroids based upon their spectral reflectance. Tedesco et. al. (1982) established the Eight-Color photometric system specifically for classifying asteroids by their surface properties. Later, Tedesco et. al. (1989) showed that a subset (U, V, and X) of the Eight-Color asteroid system, together with IRAS asteroid albedos, can be used to provide an estimate of the object's class and density. The diameter of the object can be estimated through polarization observations, observations in the thermal IR, occultations, or speckle observations. These observations, when combined with the classification, can lead to the determination of the object's mass.

Analysis of light curves can provide information on asteroid dynamics (rotation rates and pole orientations) and shape. Pole orientations have been determined for only a few of the thousands of asteroids primarily because of a lack of sufficient observational data. There are two basic approaches to pole determination: Amplitude-Magnitude and Epoch, each with several implementations (P.Magnusson, et al., 1989; J.V. Lambert, 1985). Given sufficient observational data over a wide range of viewing geometries, i.e., multiple apparitions, a reasonably reliable pole orientation can be determined to within a two-fold ambiguity. The existence of other types of observations (radar, occultation, infrared, or speckle) can greatly benefit the analysis process. Once a pole solution is available, estimates of the shape can be derived. As demonstrated by Russell (1906), an unambiguous solution for shape from light curves alone is not possible. A number of assumptions (uniform albedo, convex shape, etc.) are generally invoked to constrain the solution.

The approach employed in our future analysis for pole orientation and shape employs a

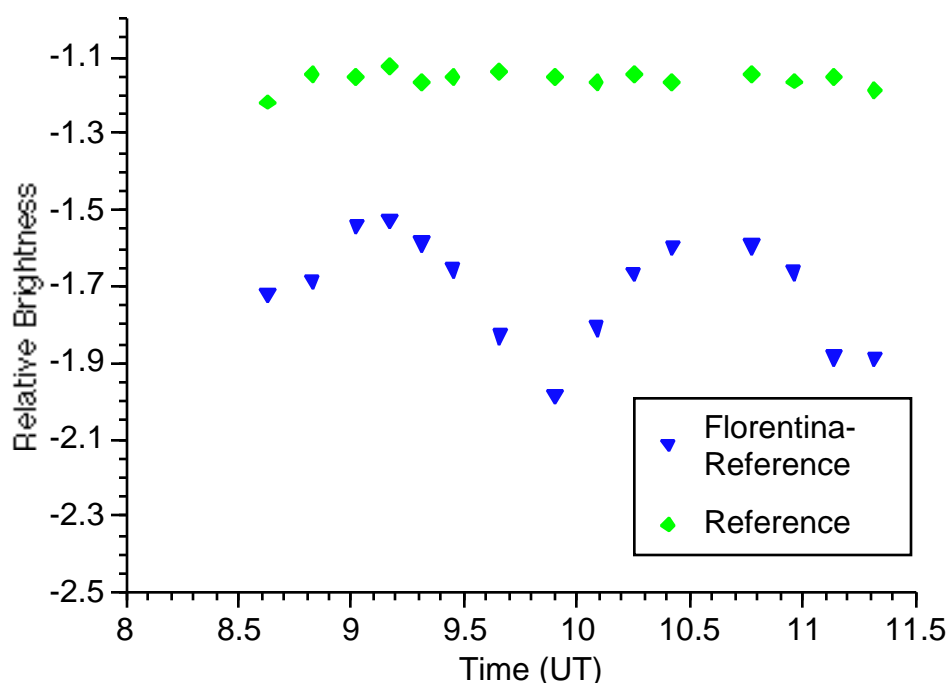
combination of techniques. The available observational data is first used to restrict the pole orientation. A simultaneous, least-squares solution is then employed to refine the pole solution and estimate the shape. The shapes are limited to simple variations of tri-axial ellipsoids, e.g., asymmetric eastern and western hemispheres, flattened regions, etc. added to reproduce observe light curve asymmetries. The ellipsoids are described by three or more parameters and are computer modeled as a collection of several thousand small, flat triangular facets, Lambert (1985). Various surface scattering functions can be used. The results obtained from this analysis of the limited observational data are not intended to represent exact or unique solutions. They are intended to provide preliminary estimates of the shapes and dynamics for use in planning future observations and as starting points for future, more detailed studies as shown in Figure 3.

**Figure 3. Simulated Asteroid Light Curve**



Phillips Laboratory has only recently started the photometric characterization work with the addition of the six position filter wheel. We have now obtained observations of portions of several light curves on 1996 FR3, 321 Florentina, 1957 Angara, 201 Penelope, 2954 Delsemme, 2017 Wesson, and 216 Kleopatra. Our initial emphasis has been on asteroids with short rotational periods and large light curve amplitudes. The results are in good agreement with previous observations. Figure 4 is a light curve obtained at MSSS of the object 321 Florentina which illustrates our photometric capability. The technique employed is differential photometry where a stable star is used as a reference and the object's magnitude is subtracted from the reference to compensate for seeing variation. Preliminary analysis of these light curves shows that these objects have periods of several hours with amplitudes of 0.4 magnitudes, in good agreement with previous observations.

**Figure 4. Light Curve of Asteroid Florentina**



**Reporting.** Since February 1995, Phillips Laboratory has been sending weekly data reports to the MPC. More than 6000 positions have been reported to date (Figure 1.) and as a result, MSSS is the 8th most productive asteroid observing site in the world. Included in the output report are the plate solution coefficients, plate scale determination, and the residuals (rms) to the fit. Typical residuals are on the order of 0.5 arc seconds, occasionally approaching 0.2 arc seconds. The plate scale has been determined to be about 0.82 arc seconds per pixel and is stable to about 0.005 arc seconds per pixel.

As part of the quality control of the data product, all observations are compared to their predicted positions and rates. The instantaneous position of an object can be determined from a single observation. A pair of observations will reveal the object's rate of motion across the sky. For follow-up observations, the rate of motion is a reliable indicator as to whether the object observed is the desired object or a different object. Because of the narrow field of view (13 arc minutes), a tasked object may not appear in the field, but a moving object may be detected near that position. The key indicator is that the moving object's rate of motion will differ from that predicted for the tasked object. When this happens, the positions and rates of the new object are compared to each of the approximately 20,000 objects in the asteroid catalog. If the object is indeed a new discovery, it is given a local AMOS designation. From its position and rate of motion, new positions for the ensuing nights are computed and the object is tasked for more observations.

Over the past several months, Phillips Laboratory has successfully applied the data analysis techniques used to determine asteroid positions to determine satellite positions as well. The measurement accuracy of the satellite data obtained with the Raven system and the 1.2 telescope using the JPL CCD is within an arcsecond. The Raven system is ready to be tested for full automation this summer. Since the Raven system is designed

to be fully automated, the O&M cost for operations is minimal. The Raven system can augment space command operations by off-loading the large telescopes. The large telescopes can be tasked to search for faint, fast, hard to find objects while the Raven system is tasked to obtain geo-sync and bright object data.

#### **4. Summary**

Phillips Laboratory has brought together a team of highly motivated and dedicated professionals with a proven track record of working with the Air Force, the academic community and NASA, to assist in the cataloging of ECAs. With the addition of the Raven systems to obtain follow-up data to refine the orbits of newly discovered objects, the large FOV sensors can remain as search sensors. The Phillips Laboratory team has also designed the Raven system to be fully automatic. This automation includes automatic scheduling via the internet, dome automation for weather and mount motion, automated observing and data collection, and automated data processing which is ready for testing this summer. The Phillips Laboratory team has utilized the advantages of COTS technology to deploy the Raven system at low acquisition and development costs, while retaining high reliability and maintainability. Through COTS technology, flexibility to upgrade the Raven system as technology advances becomes effortless. The Raven system can augment SSN operations by providing accurate sub arc second metric operational data. Smooth transition to a validated operational system has always been a design goal and with the low percentage of custom hardware and software, validation testing and configuration management costs and efforts are minimized. The synergy of the Phillips Laboratory team has resulted in a truly successful Earth Defense Research and Development project.

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